

Intraoperative Assessment of Critical Biliary Structures with Visible Range/Infrared Image Fusion

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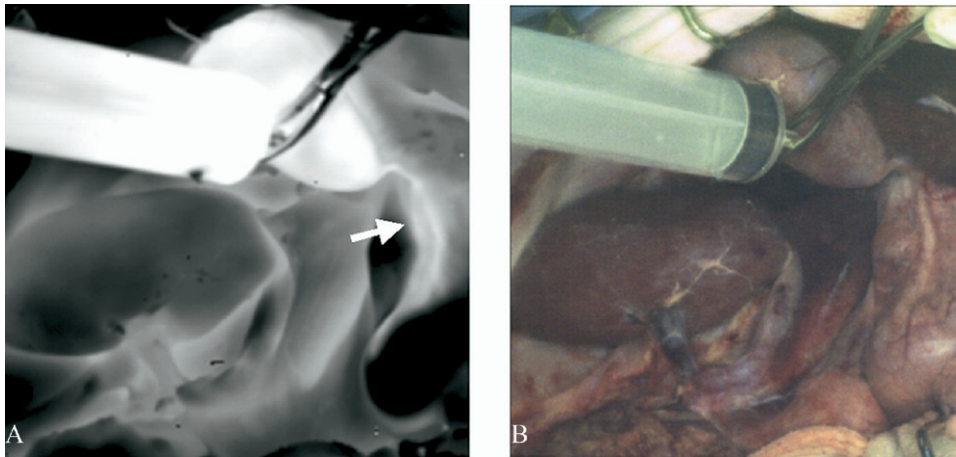


Figure 1. Visualization of a warm (39°C) intraoperative cholangiography using: (A) infrared image only. Arrow, common bile duct (CBD). (B) Visible range image only. The CBD boundaries are discernible; diffuseness is noticeable in the vicinity of the CBD boundaries.

There is considerable concern that surgical errors in laparoscopic cholecystectomy (LC) occur at the rate of approximately one injury per 200 patients,^{1,2} despite standardized training and inclusion of LC training for surgery residents.³ The timely detection of bile duct injuries (BDIs) during

LC substantially lowers morbidity, reduces hospital stays, and decreases overall costs.⁴ Mistaken recognition of biliary structures and confirmation bias contribute strongly to the surgeon's failure to avoid or recognize intraoperative injuries.⁵ Misidentifications are typically the result of an incorrect interpretation of visual data, one of the natural outcomes of the limits of human perception and cognition under laparoscopic conditions. More training or more "blame" is unlikely to reduce BDI rates.⁶ Surgeons have adopted preventive measures, such as fluoroscopy or intraoperative ultrasonography, to better define biliary anatomy during LC. These methods are limited by increased operative time, radiation exposure and cost (ie, fluoroscopy),⁷ or incomplete definition of the biliary anatomy (ie, ultrasonography).⁸ In addition, when radiopaque contrast agents are used, contrast leaks can obscure subsequent image acquisition. A real-time, radiation-free method to clearly define biliary anatomy could address these issues.

Infrared (IR) imaging uses the principles of thermography to measure and display temperature differences and changes. Studies have pointed to the clinical use of the technology in renal transplantation, neurosurgery, and

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Abbreviations and Acronyms

BDI	= bile duct injury
CBD	= common bile duct
IOC	= intraoperative cholangiography
IR	= infrared
LC	= laparoscopic cholecystectomy
PSF	= pattern selective image fusion
VR	= visible range

laparoscopic procedures⁹⁻¹¹ and advanced laparoscopic IR systems are in development. Spatial resolution of IR cameras is lower than the resolution of visible range (VR) cameras typically used during operation and viewing IR images alone requires new cognitive skills from the surgeons who must interpret them.

The objective of this study was to provide an initial assessment of the following hypotheses:

1. Visualizing IR and VR video images simultaneously while perfusing the biliary tract with warm or cold saline provides the necessary real-time functional and anatomic information to recognize the biliary anatomy and associated pathologies.
2. Real-time fusion of IR and VR video images using a tunable pattern selective image fusion (PSF) approach permits a substantially enhanced visualization of biliary structures and associated pathologies compared with other modes of presentation of IR and VR imagery.

Using an intraoperative real-time image acquisition and a VR/IR PSF system prototype developed for this study, we have performed open surgical experiments with porcine models using warm and cold saline perfusion as a contrast method and assessed the potential for enhancing the identification of biliary structures and biliary injuries intraoperatively through fused images.

METHODS

Animal model and surgical procedures

A porcine model ($n = 3$) was used to evaluate the visualization of biliary structures with VR images, IR images, and fused images. Animals were between 5 and 9 months old and weighed between 23 kg and 73 kg. All studies were performed according to National Institutes of Health Institutional Animal Care and Use Committee–approved protocol UOB-006, and all animals were maintained according to the guidelines issued by the Institute of Laboratory Animals Resources, National Research Council. General anesthesia with 1% isoflurane was administered, and laparotomy was performed with exposure of the right upper quadrant. Intraoperative cholangiography (IOC) was

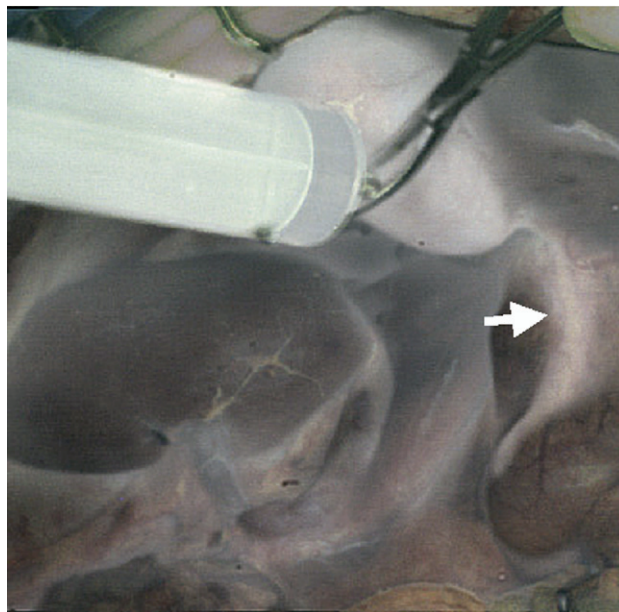


Figure 2. α -Blended composite of infrared and visible range images captured during a warm (39°C) intraoperative cholangiography. Arrow points to the common bile duct with clearly blurred boundaries.

performed through the infundibulum of the gallbladder and both cold (4°C) and warm (39°C) 20-mL saline boluses were injected into the biliary tree as contrast agents while images were collected. To simulate a common bile duct (CBD) occlusion and transcystic CBD exploration, a 3F Fogarty catheter (Edwards Life Sciences LLC) was introduced through the cystic duct, and warm and cold IOCs were repeated. Finally, to evaluate the ability of the fusion system prototype to detect injuries to the CBD, a 2-mm defect was created in the lateral wall of the CBD, 2 cm above the duodenum, and a cold IOC was performed.

Image acquisition and fusion

The intraoperative IR/VR image acquisition prototype consisted of a 3 CCD VR (up to 900 nm) color camera (model A102kc; Basler), with a resolution of $1,392 \times 1,040$ pixels per image, and a cooled midwave (3 to 5 μ) IR camera (Santa Barbara Focal Plane) with a resolution of 320×256 pixels per image. Lenses were chosen to make the fields of view in the IR and VR as similar as possible. The camera assembly included a beam-splitter, transmitting in the mid-IR spectral range (3 to 5 μ), with average transmission efficiency $>90\%$, and reflecting in the visible spectral range (450 to 750 nm) with a similar average efficiency. The beam-splitter was placed in the optical path of the IR camera, thereby optically aligning the VR and IR fields of view. Residual misalignments between the IR and VR fields of view stemming

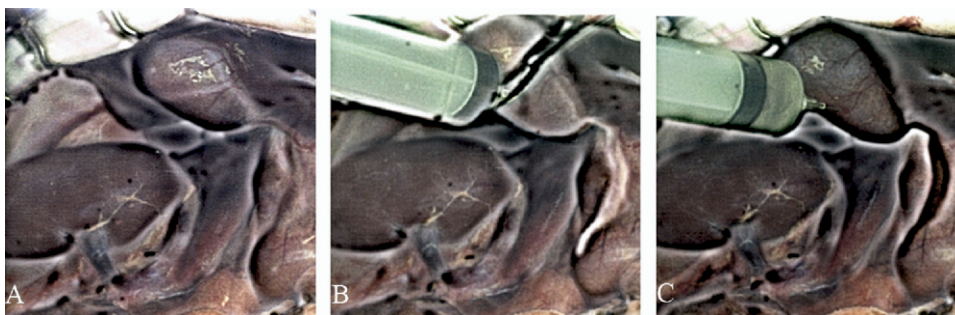


Figure 3. (A) Baseline infrared (IR)/visible range (VR) pattern selective image fusion (PSF) fused image. (B) PSF fused IR/VR image generated during a warm (39°C) intraoperative cholangiography (IOC). (C) PSF fused IR/VR image generated during a cold (4°C) IOC. The common bile duct is clearly visible, with sharp boundaries.

from small optomechanical inaccuracies were eliminated with software-based alignment interfaces. A custom LED-based ring illuminator provided uniform, heat-free illumination over the surgical area of interest. Polarizing filters permitted the attenuation or complete elimination of specular reflections in the VR images.

In the medical community, overlay methods (ie, α -blending) that treat each image as a layer in a weighted average composite are the state-of-the-art for creating a single blended image from multiple source images.^{12,13} In contrast, we exploited a real-time implementation of PSF algorithms¹⁴ developed by Sarnoff Corporation for use by the military. The PSF algorithms fuse multiresolution versions of the IR and VR images, known as image pyramids.¹⁵ For each resolution,

the pixels from the IR and VR inputs are selected individually based on a measure of the local contrast and emphasized by operator-defined gain parameters. Each resolution contributes to the final fused image through a weighted recombination process, providing operators with fine control over the selection of levels of detail (eg, fine structures and edges versus background regions) and the relative contributions of the IR and VR sources for each level of detail. This allows optimization of the display to the surgeon's preferences. Other than the initial, one-time, nonuniformity correction of the IR detector, and the one-time adjustment of the gain and offset settings of the VR camera, the system did not require any extensive preparation. It required only a single operator. IR/VR-fused images were

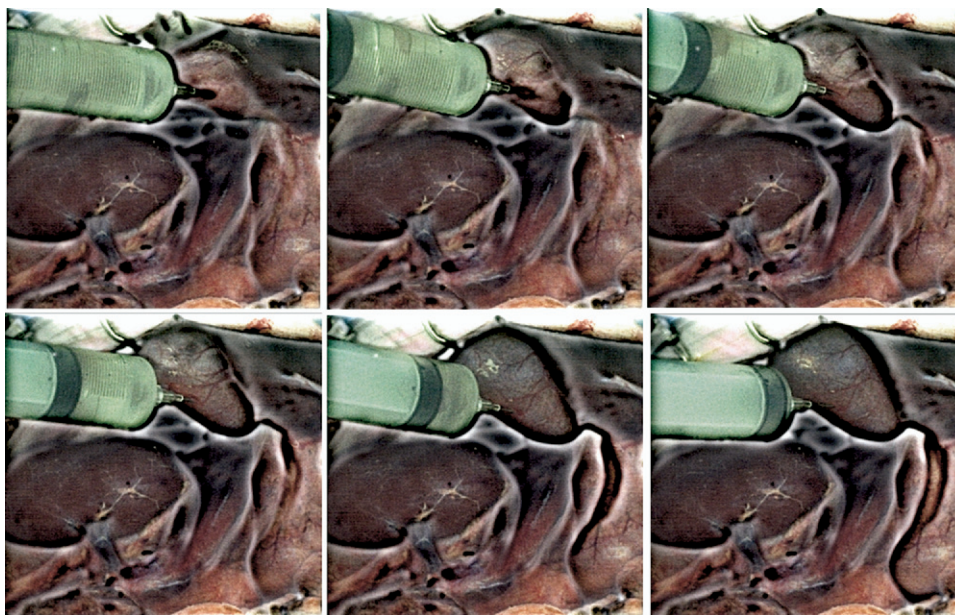


Figure 4. Sequence of six successive frames collected during a cold (4°C) intraoperative cholangiography. The infrared/visible range fusion shows sharp anatomic boundaries when dynamic thermal changes are induced by the saline perfusion.

generated in real time using the PSF algorithms. For purposes of comparison, α -blended composites (50% opacity for each source) were also generated offline from saved IR/VR data, using Adobe Photoshop.

RESULTS

The biliary system is visible in IR images alone, the duct boundaries are discernable, and diffuseness is noticeable in their vicinity (Fig. 1). The comparable VR image frame provides a high-resolution color view of the anatomic landscape and landmarks surgeons are accustomed to seeing. Figure 1 also demonstrates the difficulty of mentally fusing the paired set of images, and the benefits that would accrue from the automated construction of a single composite. Although the α -blended composite (Fig. 2) is an improvement over the side-by-side presentation of the images, the boundaries of the CBD are blurred, and the lack of contrast and washed-out colors impede precise delineation of the anatomic boundaries. Standard image processing does not substantially reduce these problems. The PSF algorithms (Figs. 3, 4) substantially improve image contrast and delineation of anatomic structures, and sharpen the duct boundaries. Unlike approaches that rely on contrast dyes, these dynamic changes can be observed repeatedly as soon as thermal equilibrium between the ducts and the surroundings is reestablished (15 to 40 seconds, depending on the chosen bolus temperature). Demarcation of saline flow restriction because of the simulated obstruction, and leakage from the site of simulated injury after cold saline perfusion are clearly apparent (Fig. 5).

DISCUSSION

The potential benefits of IR imaging include real-time, noninvasive, and continuous assessment, and added information that can help overcome the cognitive and perceptual limitations in LC. Cadeddu and colleagues¹⁶ first highlighted the potential of IR imaging for identification of biliary structures in laparoscopic surgery. These experiments focused on external irrigation of saline rather than direct injection into the biliary tract as we described here. Ultimately, the integration of IR technology into a standard laparoscope requires visualization of real-time IR and visible light images in a single display, a conclusion highlighted in another series of pilot experiments.¹⁷ This study strongly suggests that the PSF algorithms could enhance surgeons' performance in the cognitively demanding field of laparoscopic surgery. By combining complementary functional (IR) and anatomic (VR) data in a single image and, importantly, by allowing the surgeon to tailor the image fusion parameters to optimize discriminability of important features,

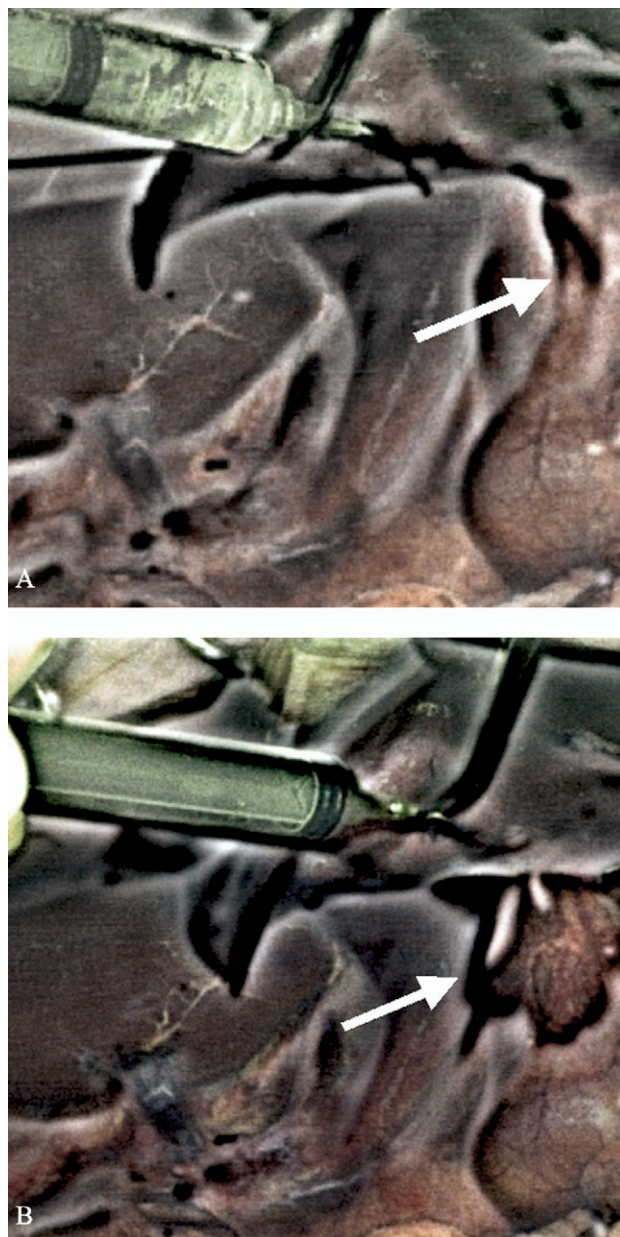


Figure 5. Infrared/visible range α -blended image (A) during a cold (4°C) intraoperative cholangiography with a simulated common bile duct (CBD) obstruction. (B) After a simulated CBD injury.

the PSF system described in this study facilitates the rapid and intuitive interpretation of the images. In this study, we have also demonstrated the ability to perform IOC in real time without any radiation exposure. By combining a PSF system with selected saline bolus injection protocols designed to enhance thermal contrast and visibility of biliary structures, we have created a promising new methodology, visible/IR operative cholangiography. Visible/IR operative cholangiography

could be used to identify BDIs in real time during the surgical procedure, eliminating the need to perform “off-line” radiographic studies. This has the potential to ensure that BDIs are not missed, and to reduce the time in operation by approximately 15%.⁵

Author Contributions

Study conception and design: Hanna, Gorbach, Gage, Pinto, Silva

Acquisition of data: Hanna, Silva, Gilfillan, Elster

Analysis and interpretation of data: Hanna, Gorbach, Silva, Gilfillan, Elster

Drafting of manuscript: Hanna, Gilfillan, Elster

Critical revision: Gorbach, Gage, Pinto, Silva, Kirk

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REFERENCES

1. Sarmiento JM, Farnell MB, Nagorney DM, et al. Quality-of-life assessment of surgical reconstruction after laparoscopic cholecystectomy-induced bile duct injuries: what happens at 5 years and beyond? *Arch Surg* 2004;139:483–488; discussion 488–489.
2. Walsh RM, Henderson JM, Vogt DP, et al. Trends in bile duct injuries from laparoscopic cholecystectomy. *J Gastrointest Surg* 1998;2:458–462.
3. Francoeur J, Wiseman K, Buczkowski AK, et al. Surgeons' anonymous response after bile duct injury during cholecystectomy. *Am J Surg* 2003;185:468–475.
4. Savader SJ, Lillemoe KD, Prescott CA, et al. Laparoscopic cholecystectomy-related bile duct injuries: a health and financial disaster. *Ann Surg* 1997;225:268–273.
5. Traverso LW. Risk factors for intraoperative injury during cholecystectomy: an ounce of prevention is worth a pound of cure. *Ann Surg* 1999;229:458–459.
6. Way L, Stewart L, Gantert W, et al. Causes and prevention of laparoscopic bile duct injuries. *Ann Surg* 2003;237:460–469.
7. Massarweh NN, Flum DR. Role of intraoperative cholangiography in avoiding bile duct injury. *J Am Coll Surg* 2007;204:656–664.
8. Catheline J, Rizk N, Champault G. A comparison of laparoscopic ultrasound versus cholangiography in the evaluation of the biliary tree during laparoscopic cholecystectomy. *Eur J Ultrasound* 1999;10:1–9.
9. Roberts WW, Dinkel TA, Schulam PG, et al. Laparoscopic IR imaging. *Surg Endosc* 1997;11:1221–1223.
10. Gorbach A, Simonton DA, Hale D, et al. Objective, real-time intraoperative assessment of renal perfusion using IR imaging. *Am J Transplant* 2003;3:988–993.
11. Gorbach A, Heiss JD, Kopylev L, Oldfield EH. Intraoperative IR imaging of brain tumors. *J Neurosurg* 2004;101:960–969.
12. Bankman IN, ed. Handbook of medical imaging. Processing and analysis. Burlington, MA: Academic Press; 2000.
13. De Grand AM, Frangioni JV. An operational near-infrared fluorescence imaging system prototype for large animal surgery. *Technol Cancer Res Treat* 2003;2:553–562.
14. Burt PJ. A gradient pyramid basis for pattern selective image fusion. The Society for Information Displays International Symposium Digest of Technical Papers 1992;23:467–470.
15. Burt P, Adelson E. The Laplacian pyramid as a compact image code. *IEEE Trans Commun* 1983;COM-31:532–540.
16. Cadeddu JA, Jackman SV, Schulman PG. Laparoscopic IR imaging. *J Endourol* 2001;15:111–116.
17. McHone B, Gorbach A, Liu J, et al. Real-time imaging of the common bile duct using infrared technology in a porcine model [abstract]. Annual Meeting of the Society of American Gastrointestinal and Endoscopic Surgeons, Las Vegas, NV, April 2007.

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